COLLEGE OF SCIENCE
GEOSCIENCES
VIRGINIA TECH

MONITORING, MODELING, AND PROJECTING VERTICAL LAND MOTION: IMPLICATIONS FOR RELATIVE SEA LEVEL RISE AND COASTAL FLOODING

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PROF. SUSANNA WERTH
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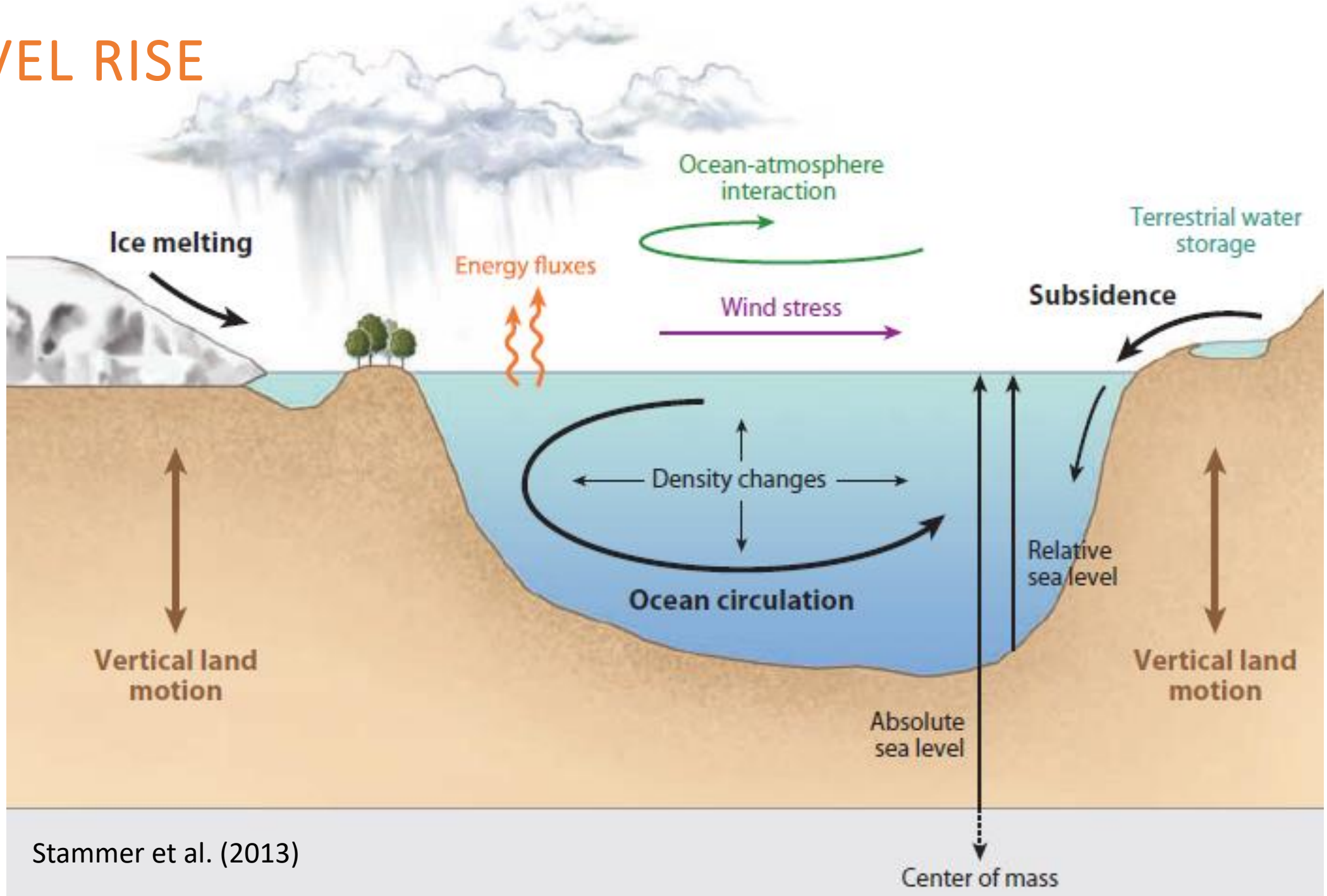
EMMA BLACKWELL

USGS
science for a changing world

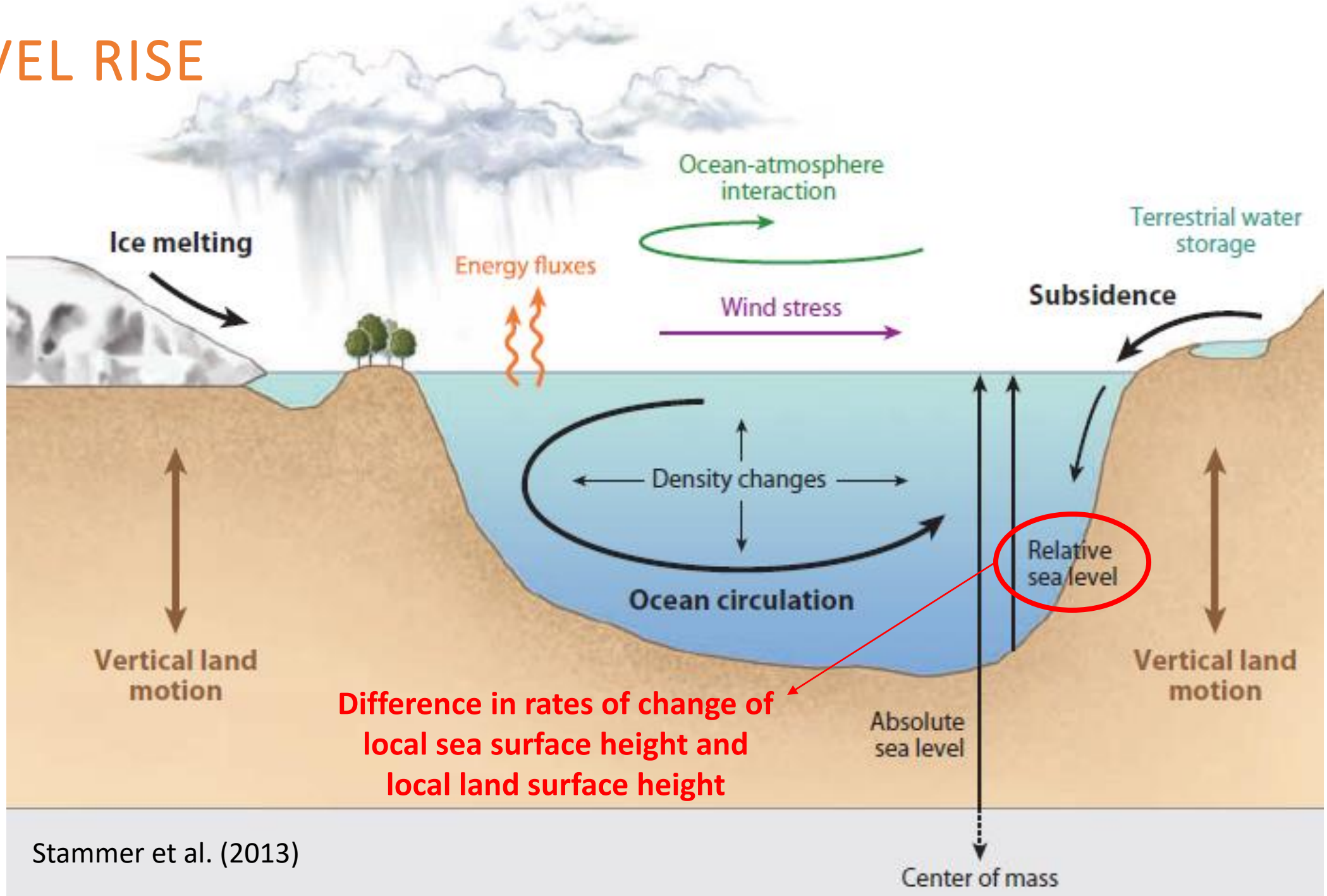
NASA

SEA LEVEL RISE



Stammer et al. (2013)

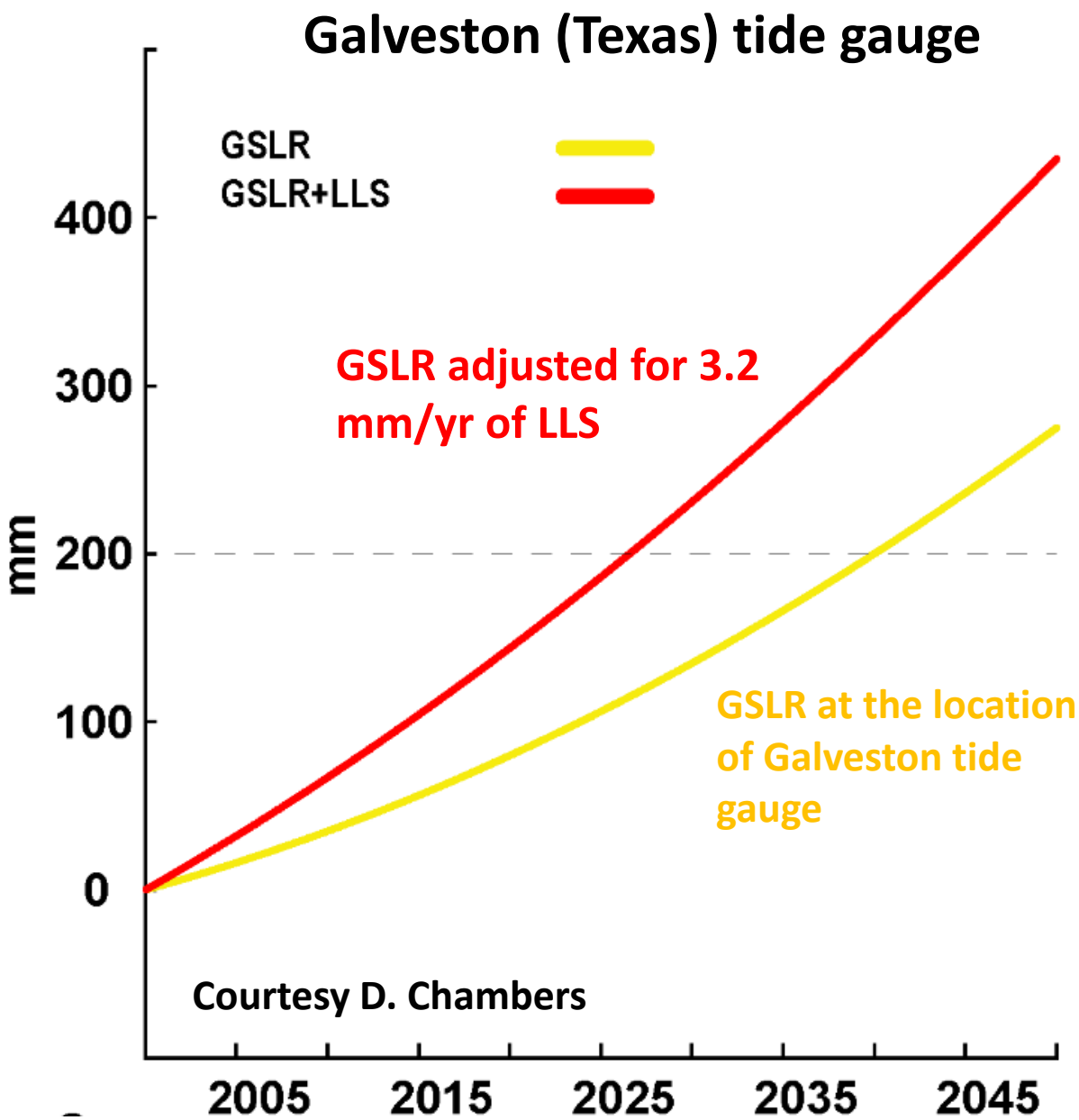
SEA LEVEL RISE



Stammer et al. (2013)

RELATIVE SEA LEVEL RISE

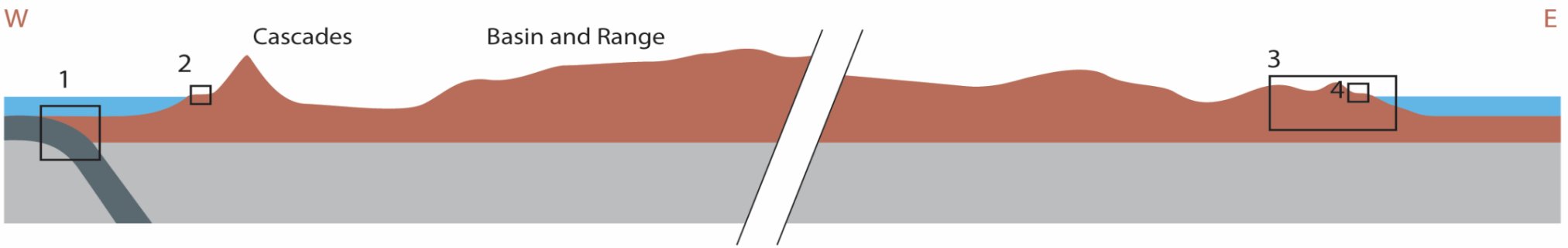
- Its rate can be much faster than the Global Mean Sea Level rise rate of ~3.3 mm/yr due to land subsidence.
- Frequency of flooding is projected to double across most U.S. coastlines with just 10-20 cm of local SLR [Vitousek et al., 2017].



Shirzaei et al. (2020, Nature Reviews)

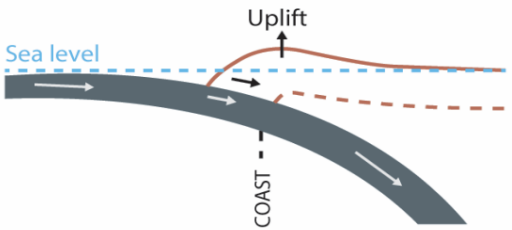
DRIVERS OF LAND SUBSIDENCE

Shirzaei et al. (2020, Nature Reviews)

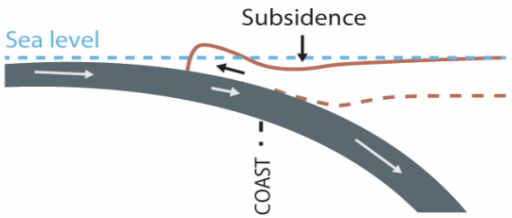


1. Tectonic Uplift/Subsidence

(a) Between events

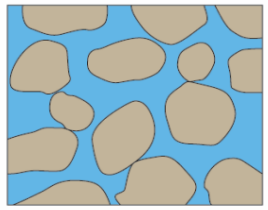


(b) Earthquake

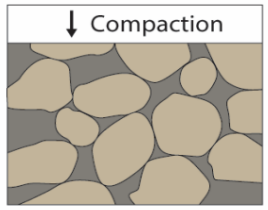


2. Fluid Extraction

(a) Before pumping

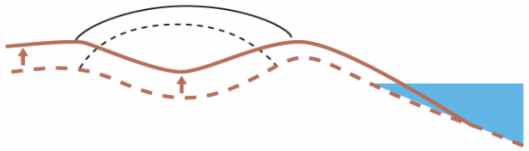


(b) After pumping



3. Glacial Isostatic Adjustment/ Sediment Loading

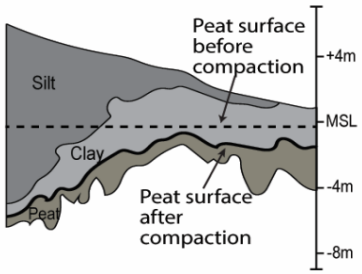
(a) Melting ice sheet/Removing sediment



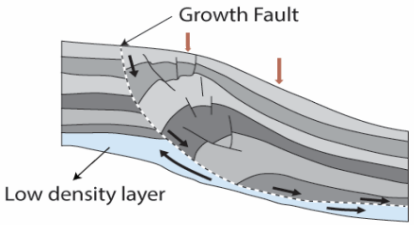
(b) New solid Earth surface

4. Sediment Compaction/ Faulting

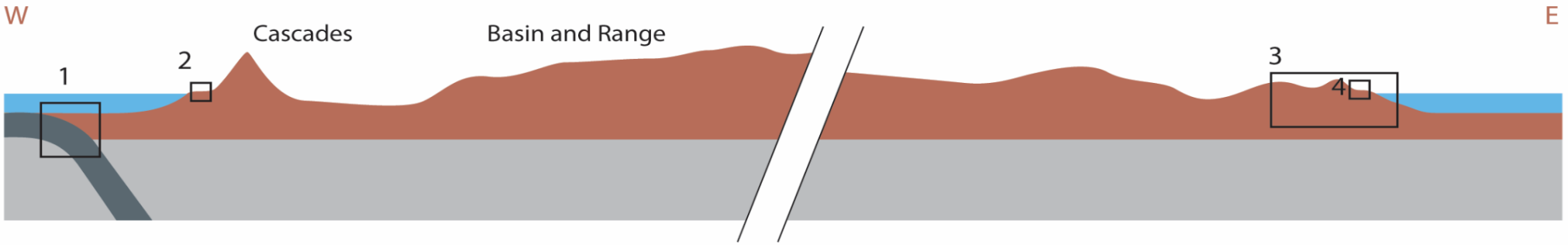
(a) Compaction



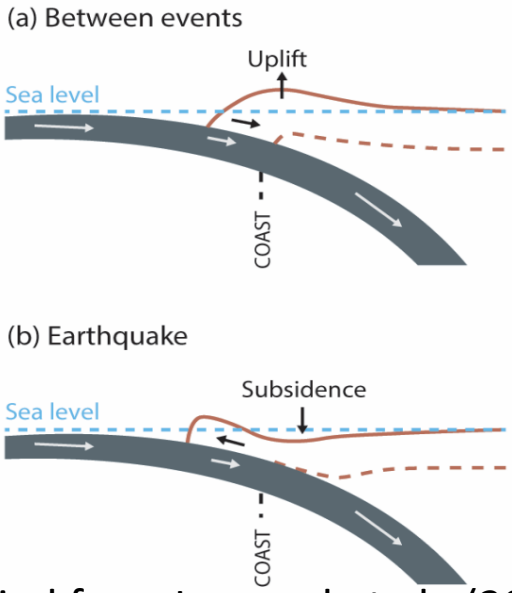
(b) Faulting



DRIVERS OF LAND SUBSIDENCE: TECTONICS



1. Tectonic Uplift/Subsidence

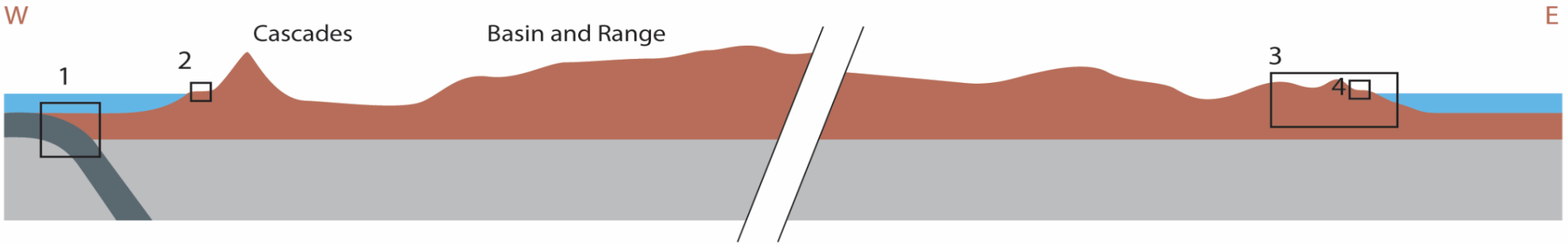


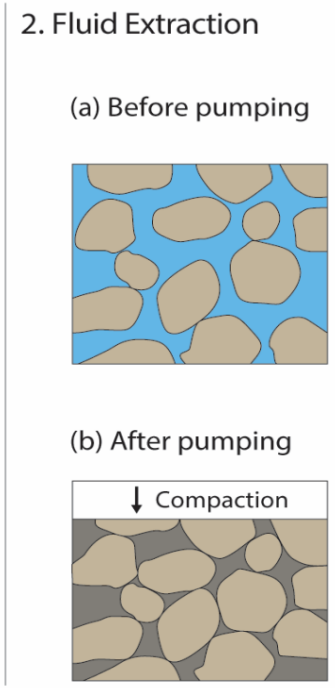
- Interseismic period: The overriding plate is squeezed producing compressional stress and uplift.
- Earthquake: the accumulated stress is released resulting in sudden horizontal motion and subsidence.
- Uplift or subsidence: Depends on location of the coastline relative to the slip patch.

Modified from Leonard et al., (2004)

Shirzaei et al. (2020, Nature Reviews)

DRIVERS OF LAND SUBSIDENCE: AQUIFER COMPACTION





Shirzaei et al. (2020, Nature Reviews)

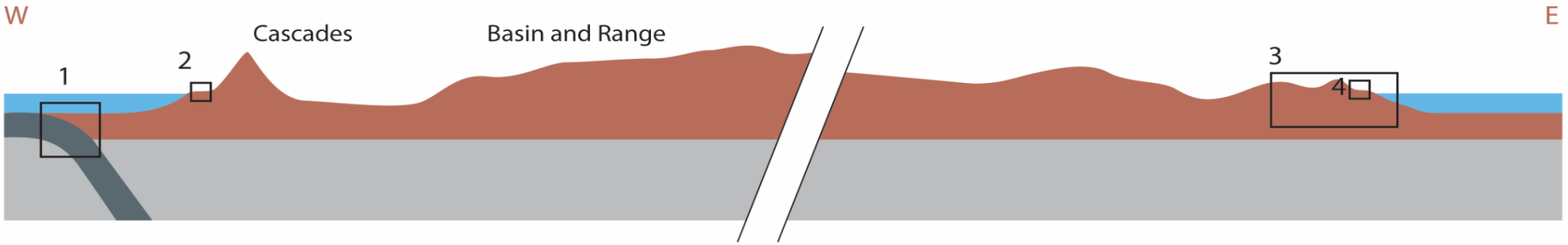
This deformation is

- Governed by the effective stress, i.e., normal stress minus pore pressure.
- Often local scale but can be fast and temporally variable.

Galloway and Burbey, (2011)

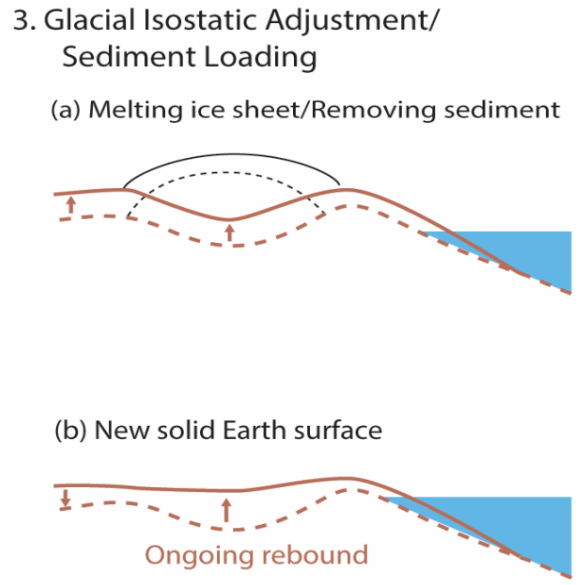
DRIVERS OF LAND SUBSIDENCE: GIA

Shirzaei et al. (2020, Nature Reviews)



- ~1 cm/yr uplift in Scandinavia and North America at the locations of the former ice sheets.
- ~1-2 mm/yr subsidence around the edges of the former ice sheets.

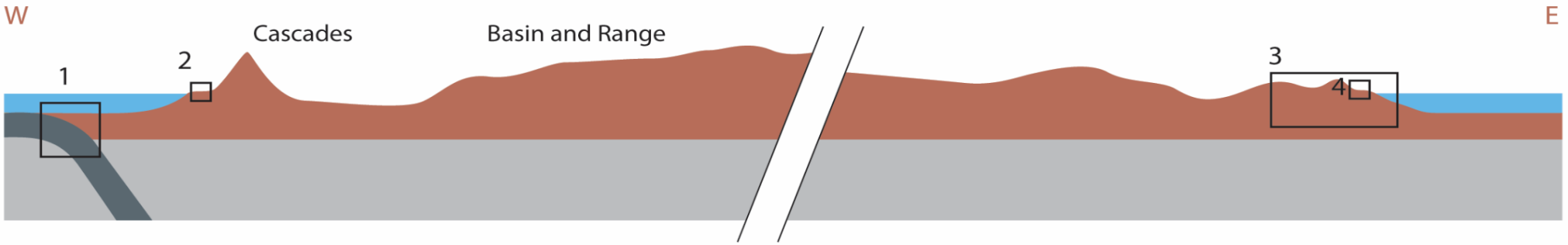
Lidberg et al., (2010); Sella et al., (2007)



Modified from Whitehouse, (2018)

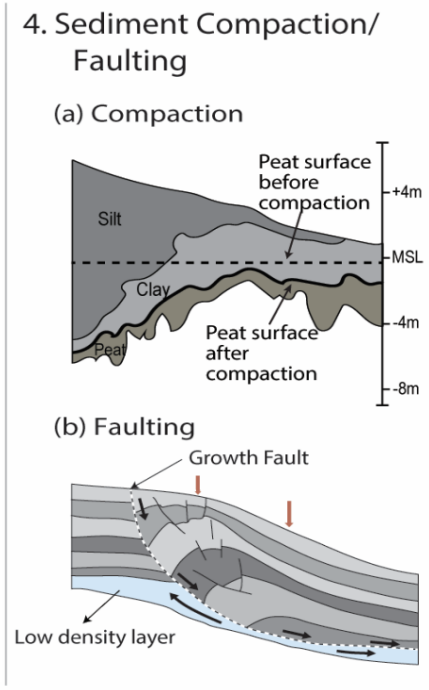
DRIVERS OF LAND SUBSIDENCE: SEDIMENT COMPACTION AND FAULTING

Shirzaei et al. (2020, Nature Reviews)



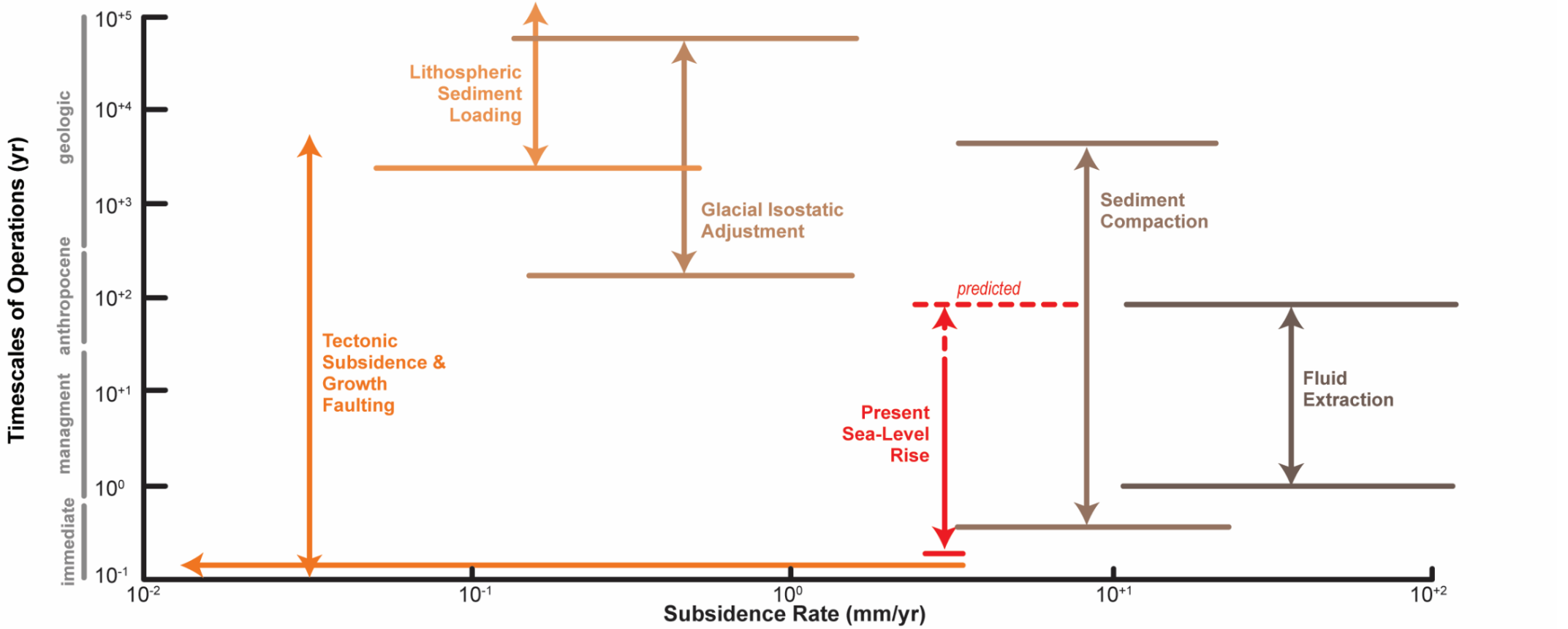
- Compaction of loose sediments under their own weight can also cause coastal subsidence.
- The sediment compaction can continue for decades to centuries and affects most sedimentary basins.

Kooi and De Vries, (1998)



SUBSIDENCE RATE AND TIME SCALE

Shirzaei et al. (2020, Nature Reviews)



Modified from Allison et al. (2016)

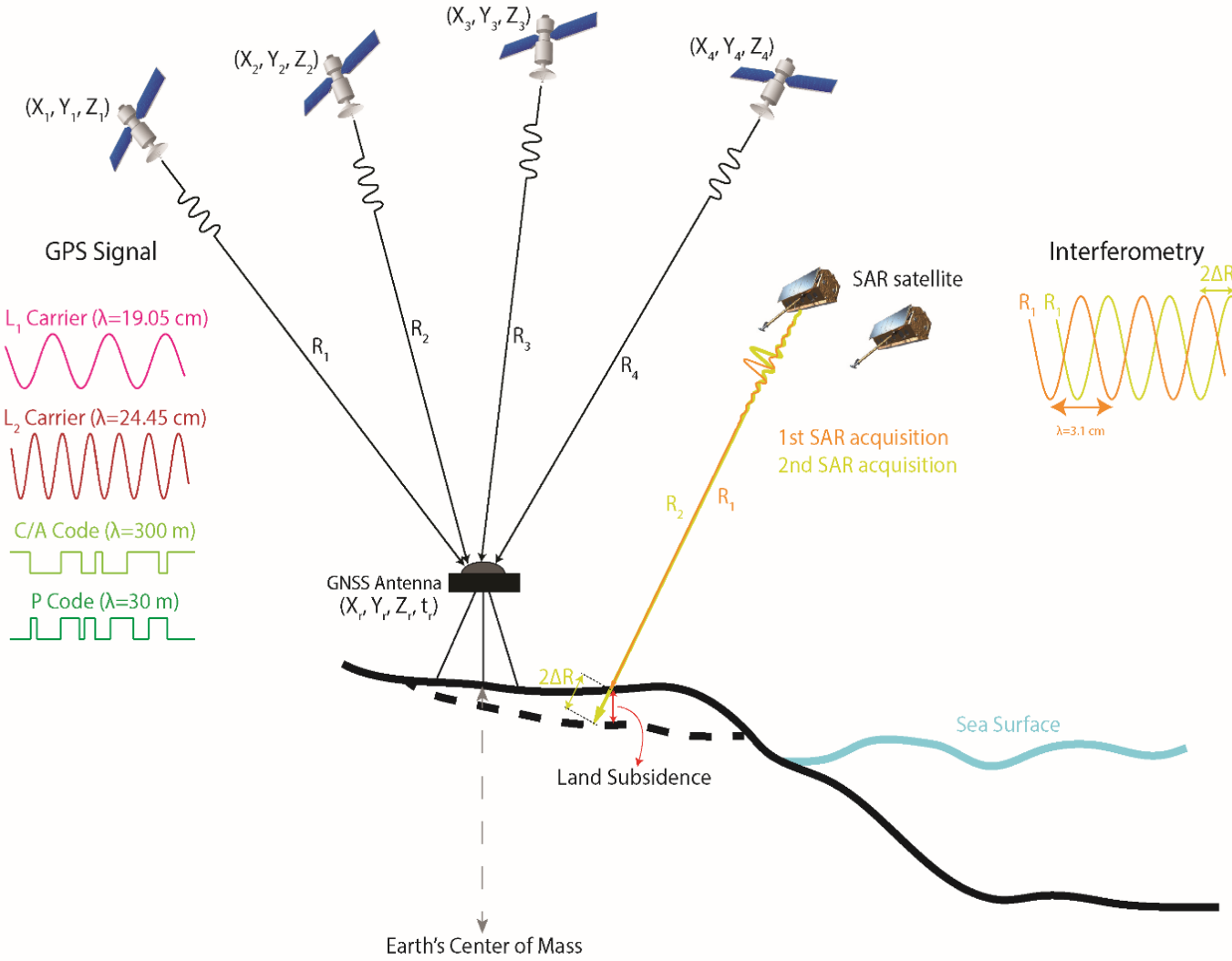
MEASURING LAND SUBSIDENCE

Challenges:

- Spatially expansive (100s of km) observations at management relevant resolution (10s of m) are hard to obtain.
- Measurements must be in a global reference frame.

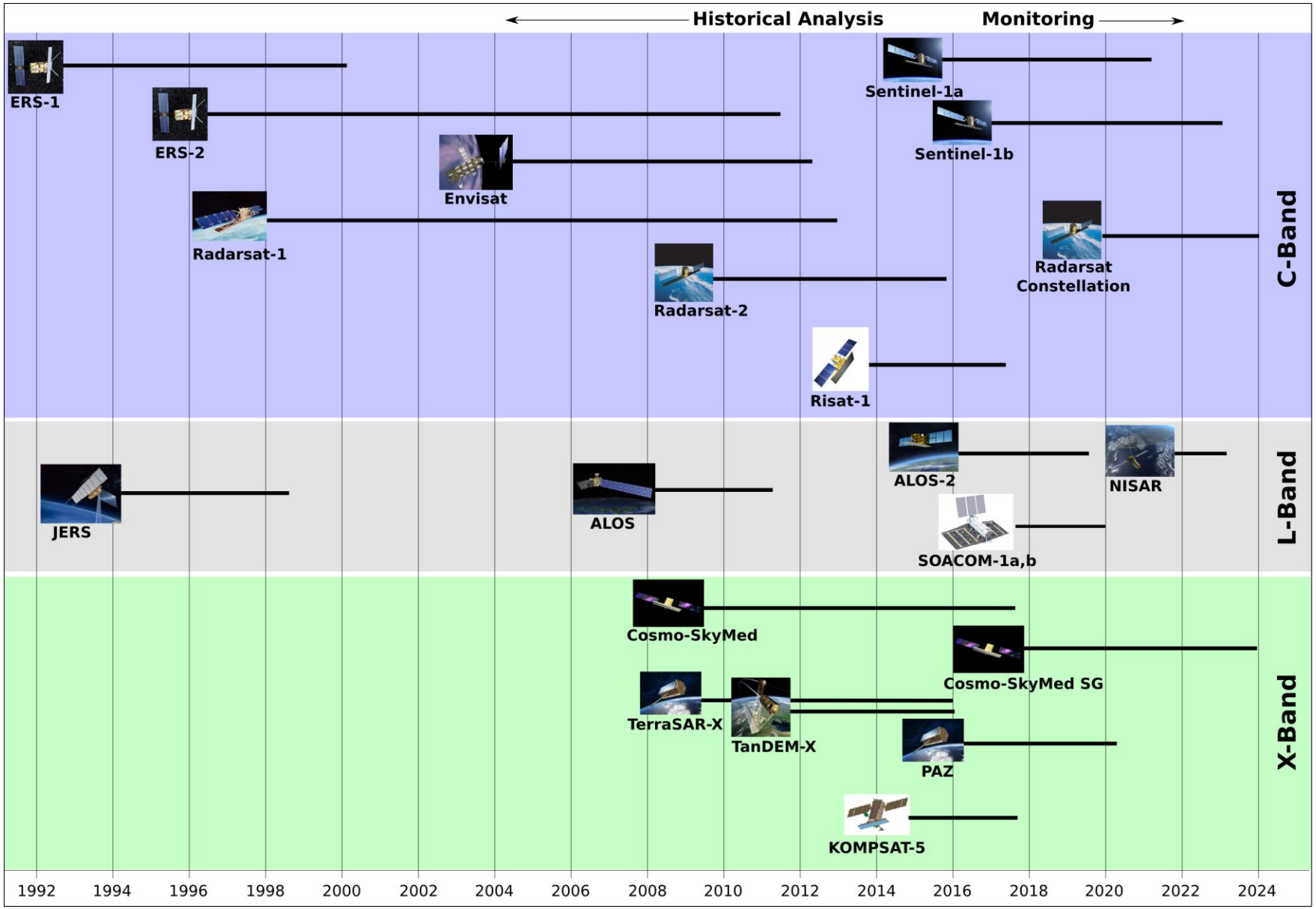
Opportunities:

- GNSS offers long-term stability, vector displacements, and better temporal coverage.
- InSAR provides the extensive spatial coverage.



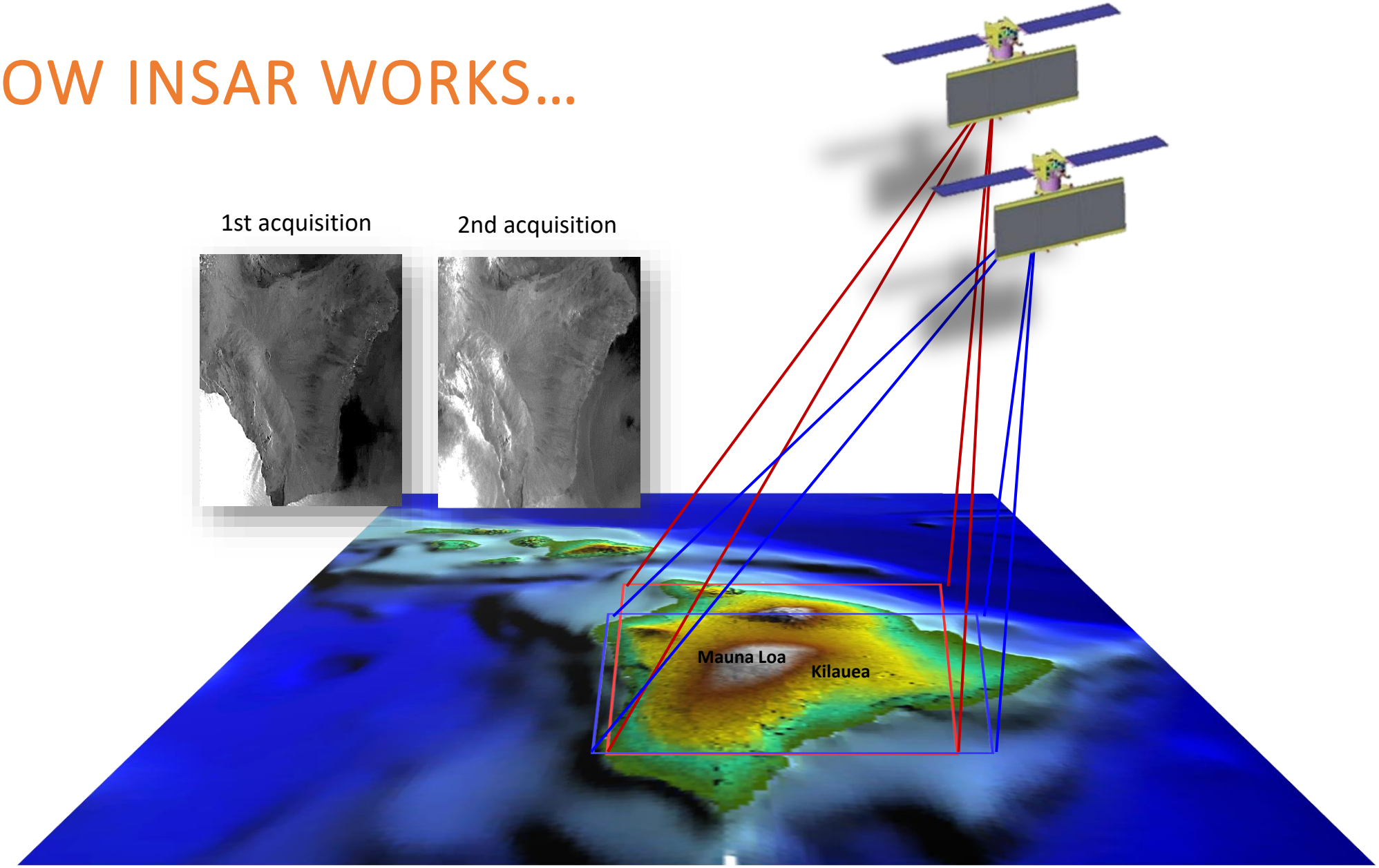
Shirzaei et al. (2020, Nature Reviews)

PAST, CURRENT AND PLANNED SAR MISSIONS

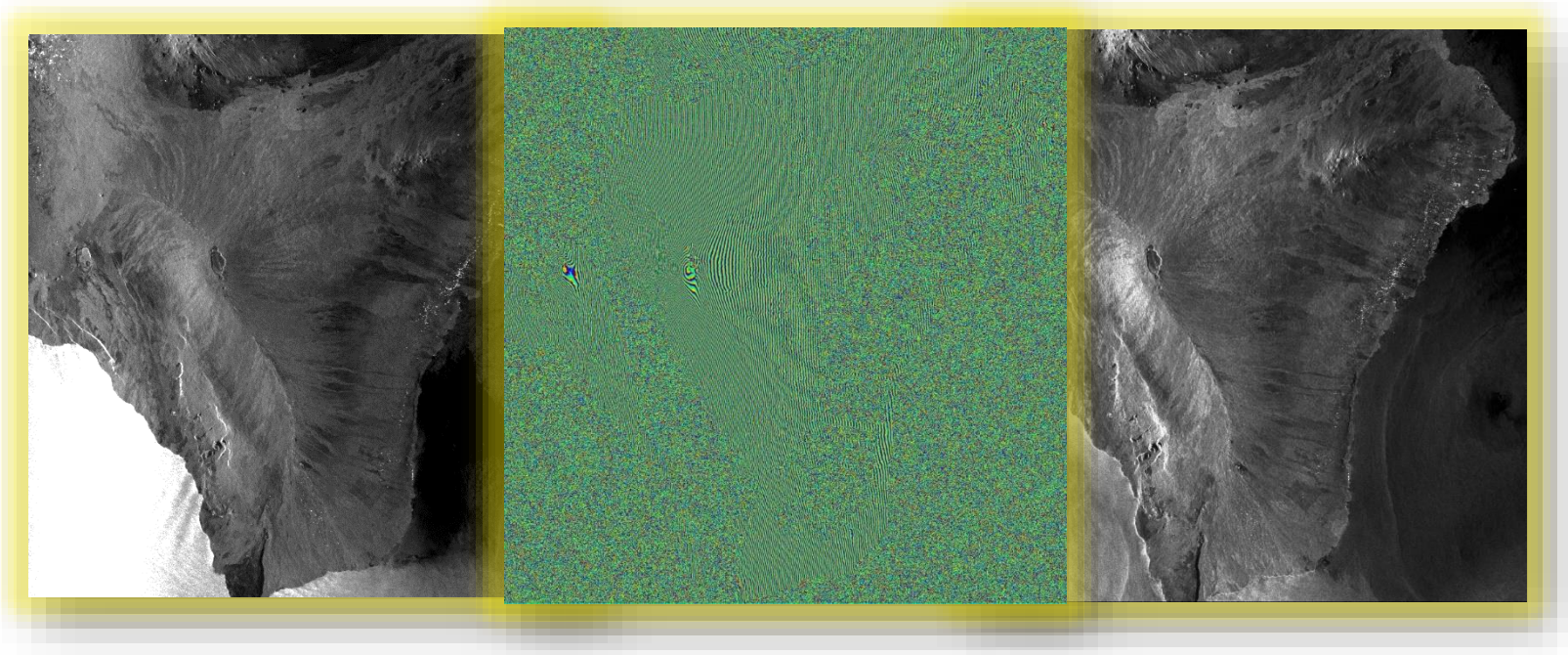


Courtesy: UNAVCO

HOW INSAR WORKS…

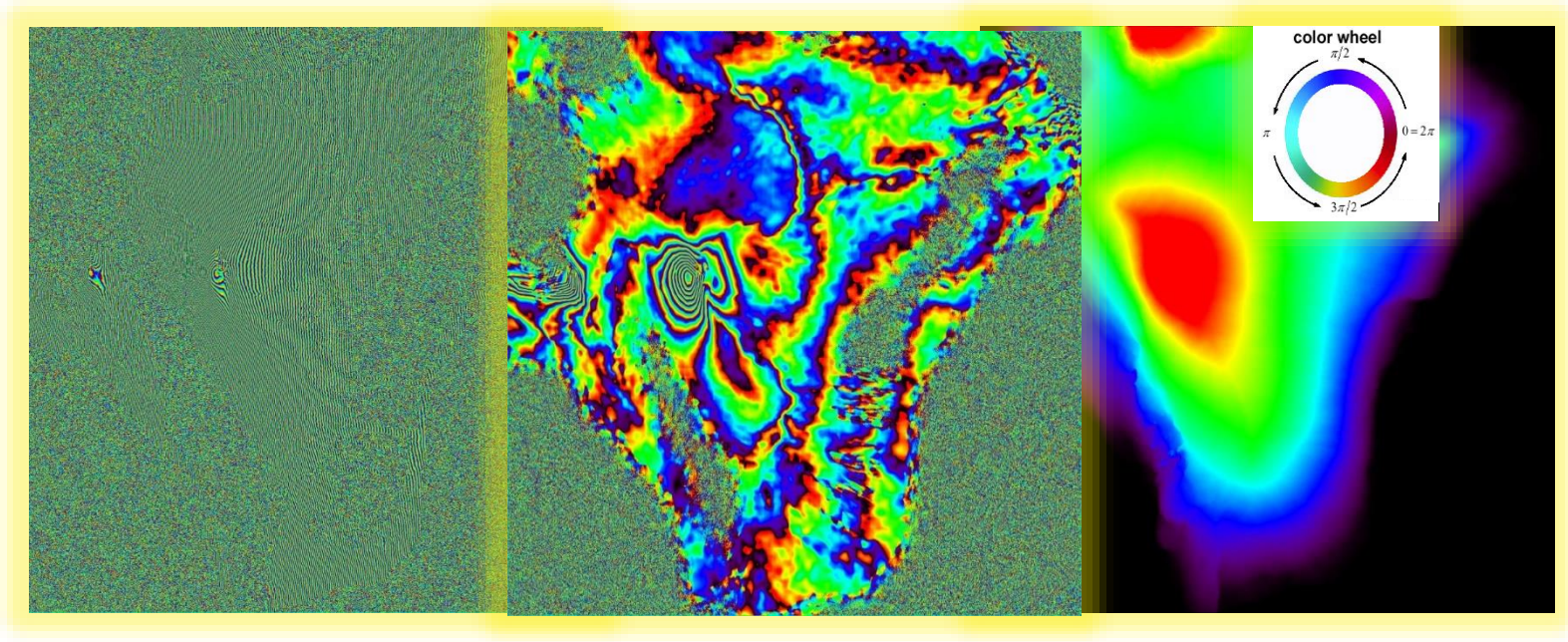


INTERFEROGRAM GENERATION



1st image Multiply (X) 2nd image

DIFFERENTIAL INTERFEROGRAM GENERATION



Int.

DEM

TAKE-HOME MESSAGES

- Land subsidence exacerbates the hazards and risks associated with the sea-level rise.

- Several natural and anthropogenic factors drive land subsidence:
  - Including tectonics, aquifer, reservoir and sediment compaction, GIA and SIA.

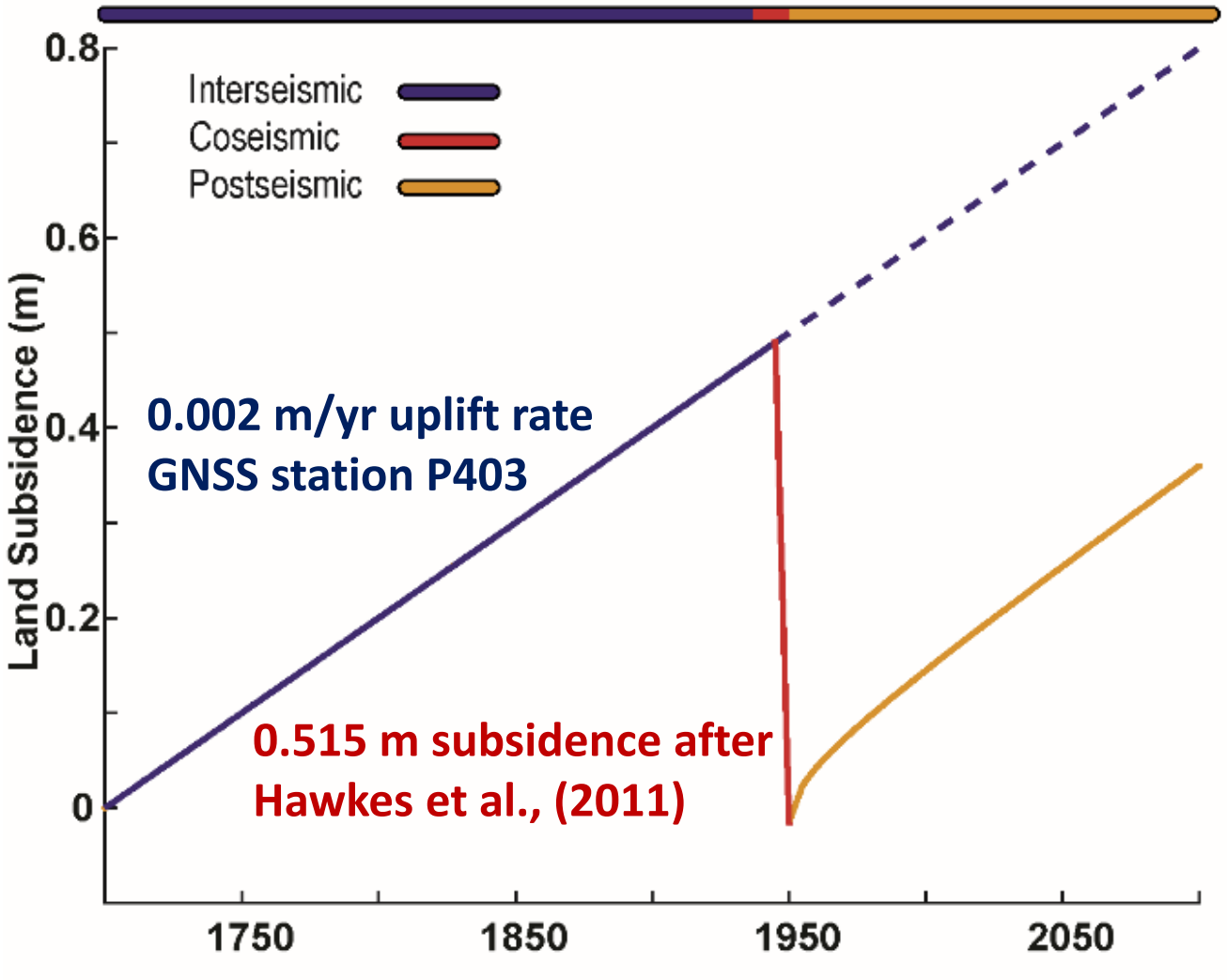
- InSAR enabled measuring the contemporary rate of subsidence at management relevant resolution.

PROJECTIONS OF LAND SUBSIDENCE

- Required for estimating future relative SLR and flooding hazards.
- In theory, these projections can be obtained by using models, calibrated using observations of the contemporary rate of land subsidence.
- In practice, this is a challenging task because the physical and socioeconomic factors driving the subsidence are not stationary and may vary over time.

PROJECTIONS OF LAND SUBSIDENCE: TECTONICS

- Challenging because of the unpredictability of future earthquakes.

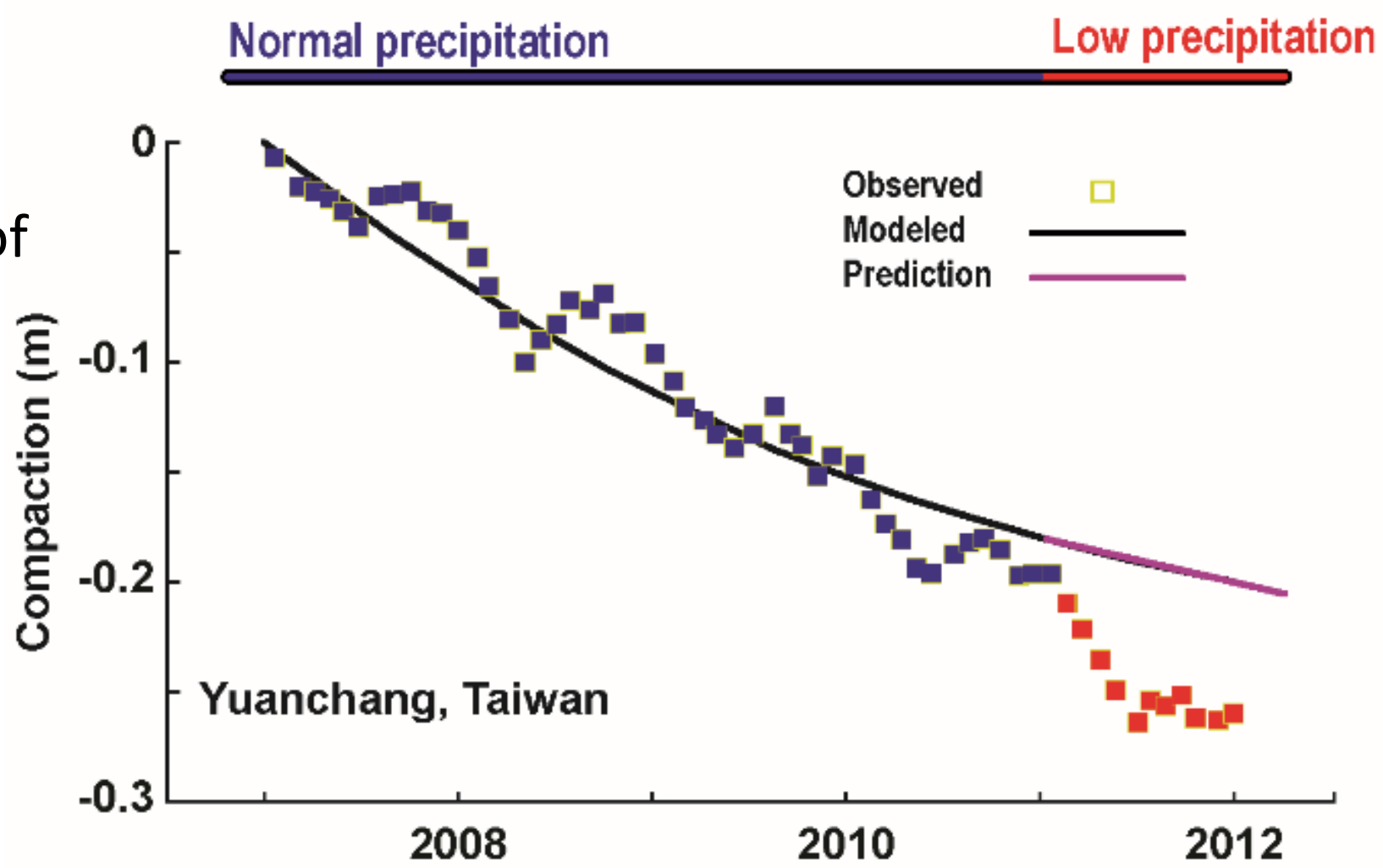


Cascadia Subduction Zone

Shirzaei et al. (2020, Nature Reviews)

PROJECTIONS OF LAND SUBSIDENCE: AQUIFER COMPACTION

- Challenging because of subsidence is very local scale but can be both rapid and temporally variable.



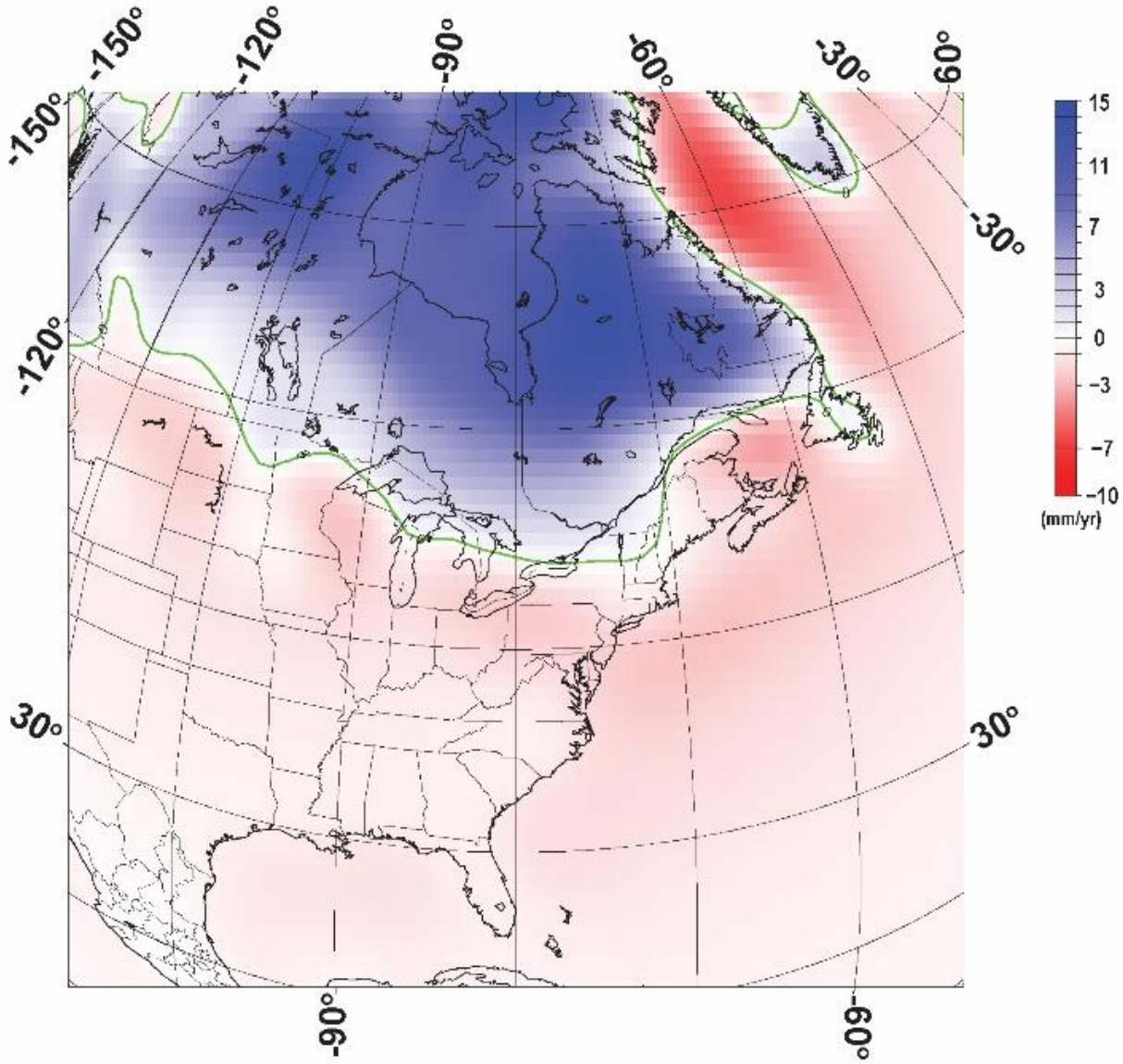
Yuanchang, Taiwan, modified from Wang et al., (2015)

Shirzaei et al. (2020, Nature Reviews)

PROJECTIONS OF LAND SUBSIDENCE: GIA

- NOT challenging because GIA from the continental deglaciations can be considered near steady over a century.

Lidberg et al., (2010); Sella et al., (2007)



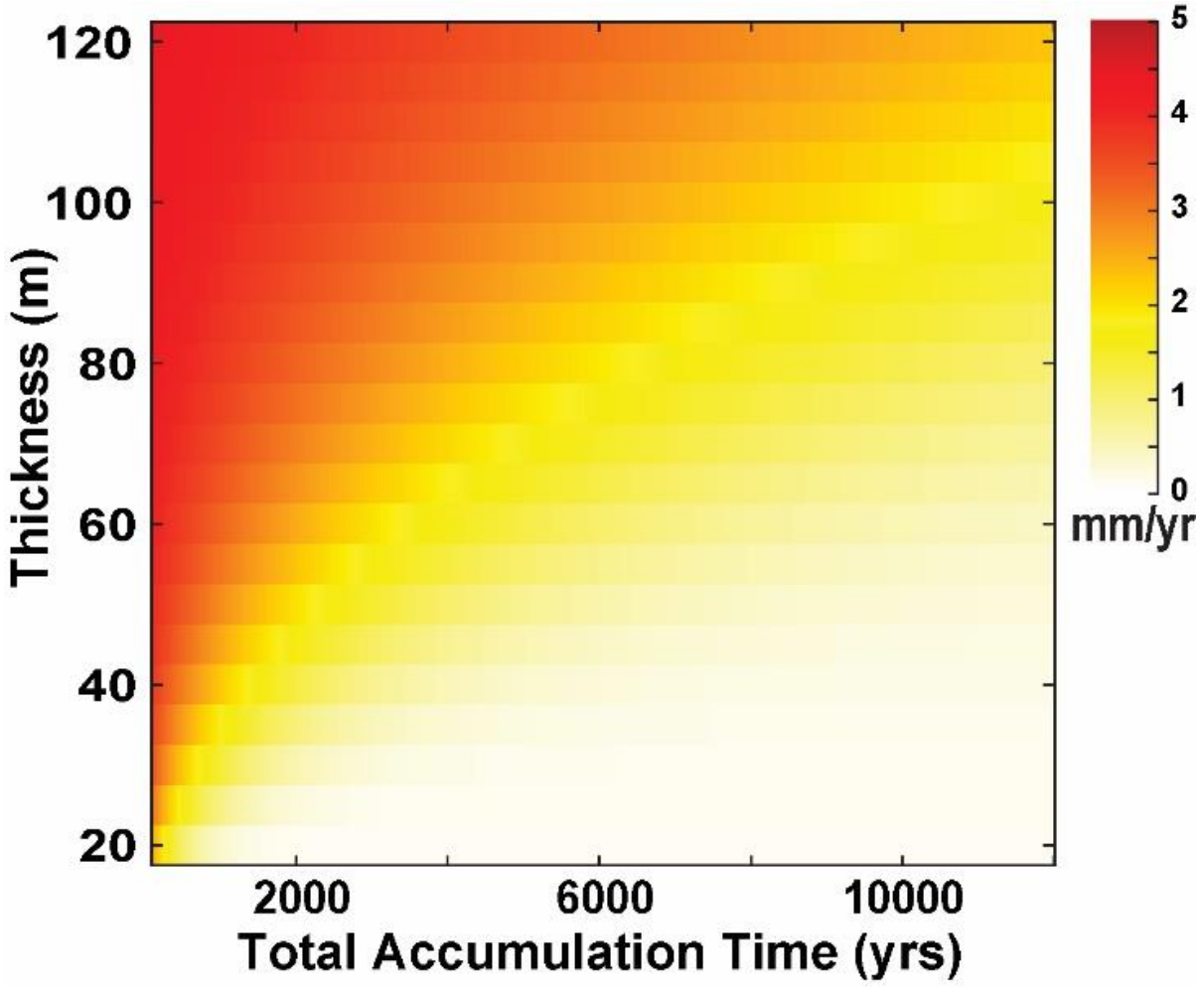
Modified from Peltier et al., (2015)

Shirzaei et al. (2020, Nature Reviews)

PROJECTIONS OF LAND SUBSIDENCE: SEDIMENT COMPACTION

- Medium challenging, although its contributions depends on local geology, sedimentation thickness, and accumulation rate but often it can be considered steady.

Kooi and De Vries, (1998)



Shirzaei et al. (2020, Nature Reviews)

Modified from Meckel et al., (2006)

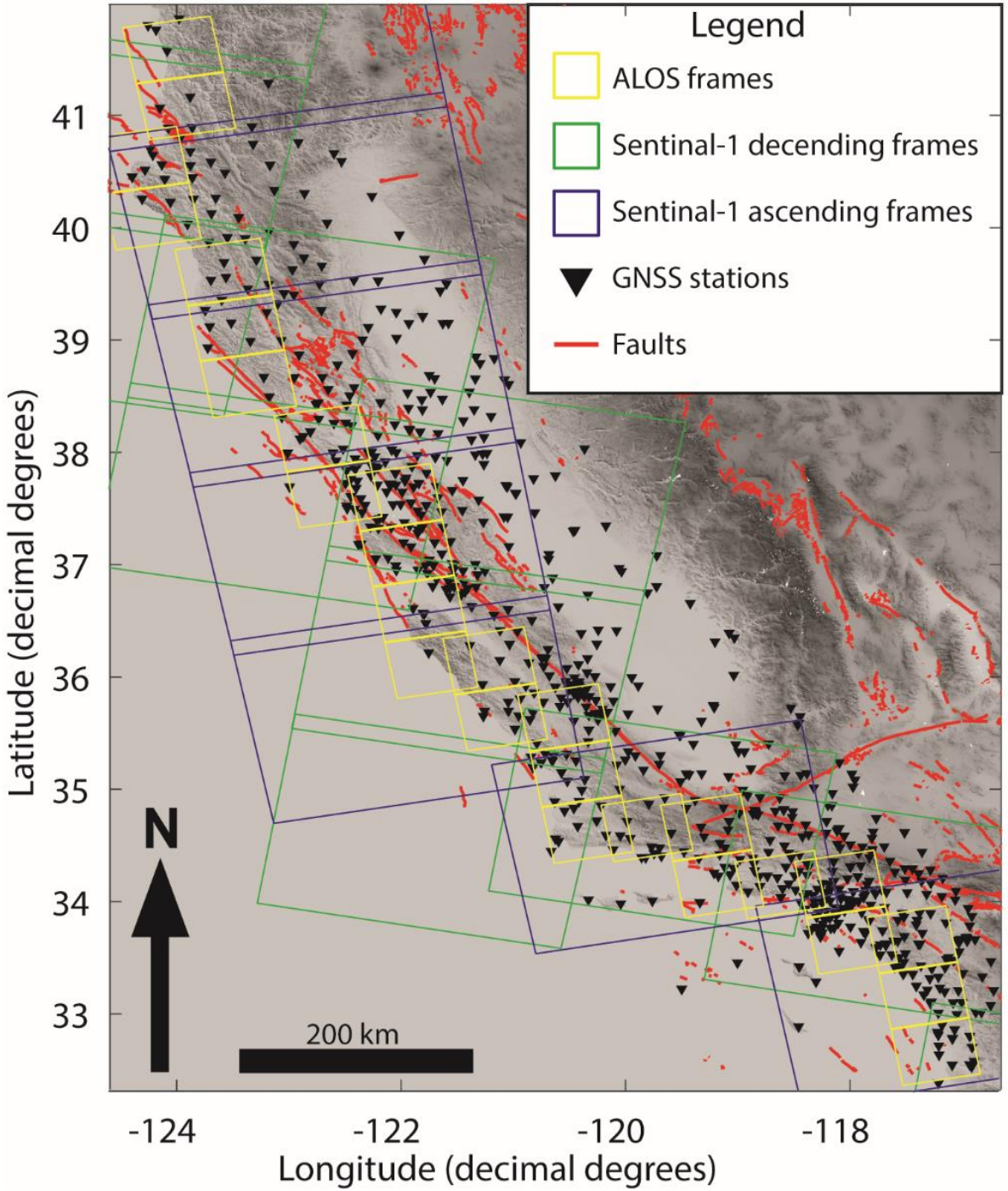
TAKE-HOME MESSAGES

- Among factors driving land subsidence, the tectonic and aquifer/reservoir compaction processes are not steady, where as GIA is mostly monotonic.

- To develop climate adaptation strategies and flood resilience plans;
  - Future work is needed to develop multi-objective land subsidence forecast models
  - These models must integrate the underlying physical processes with socioeconomic factors and climatic forcing.
  - These models are calibrated using contemporary observations.

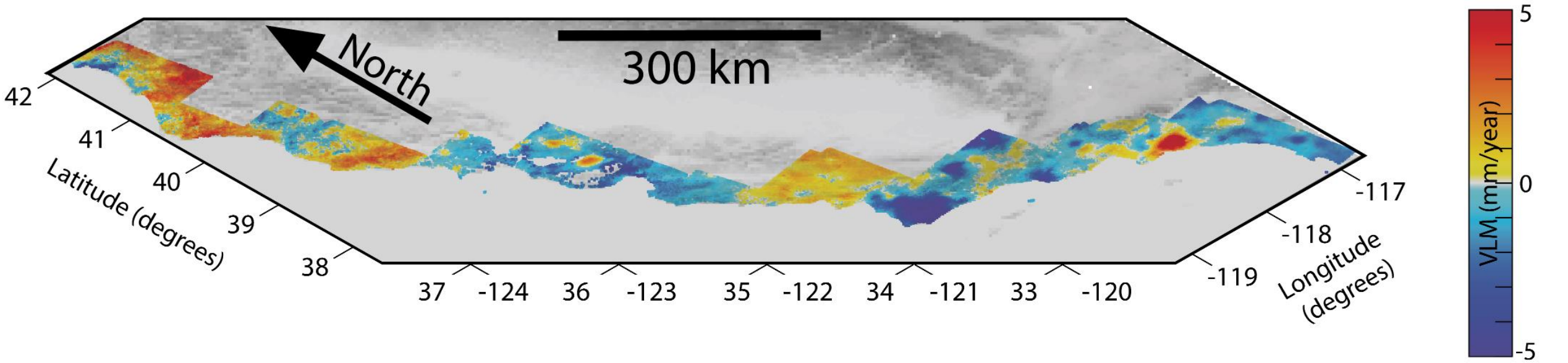
CALIFORNIA CASE STUDY

- ALOS L-band ascending 2007-2011
- Sentinel-1A/B C-band ascending and descending 2014-2019
- Global Navigation Satellite System (GNSS)



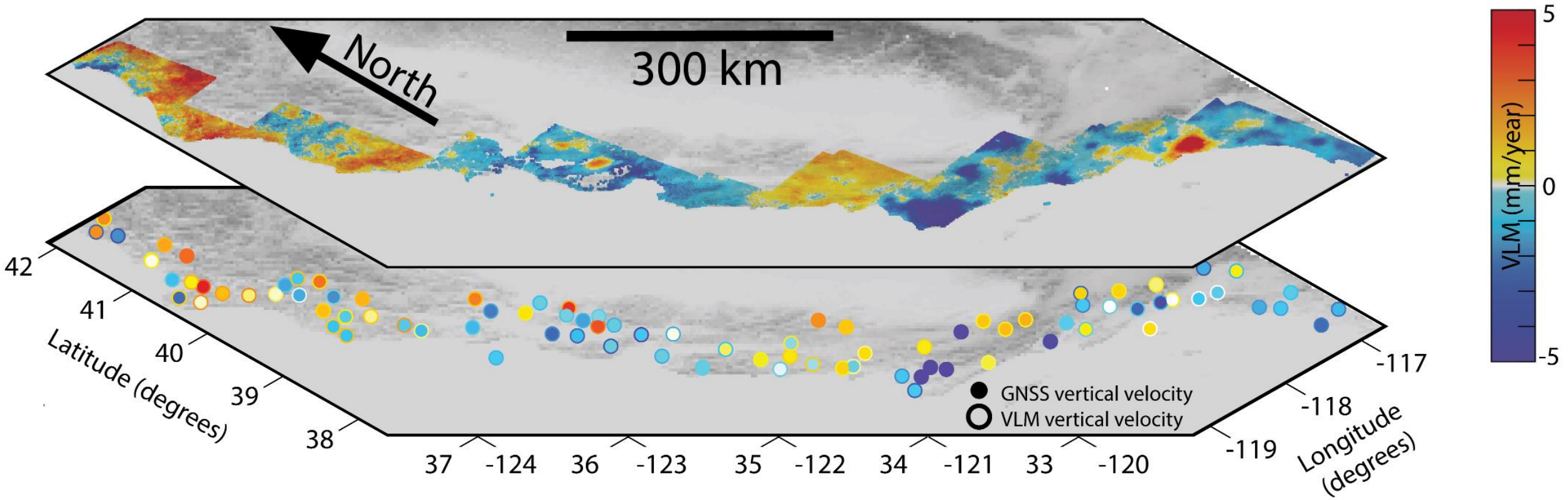
Blackwell, Shirzaei et al., (2020, Science Ad)

CALIFORNIA COAST VLM RATE



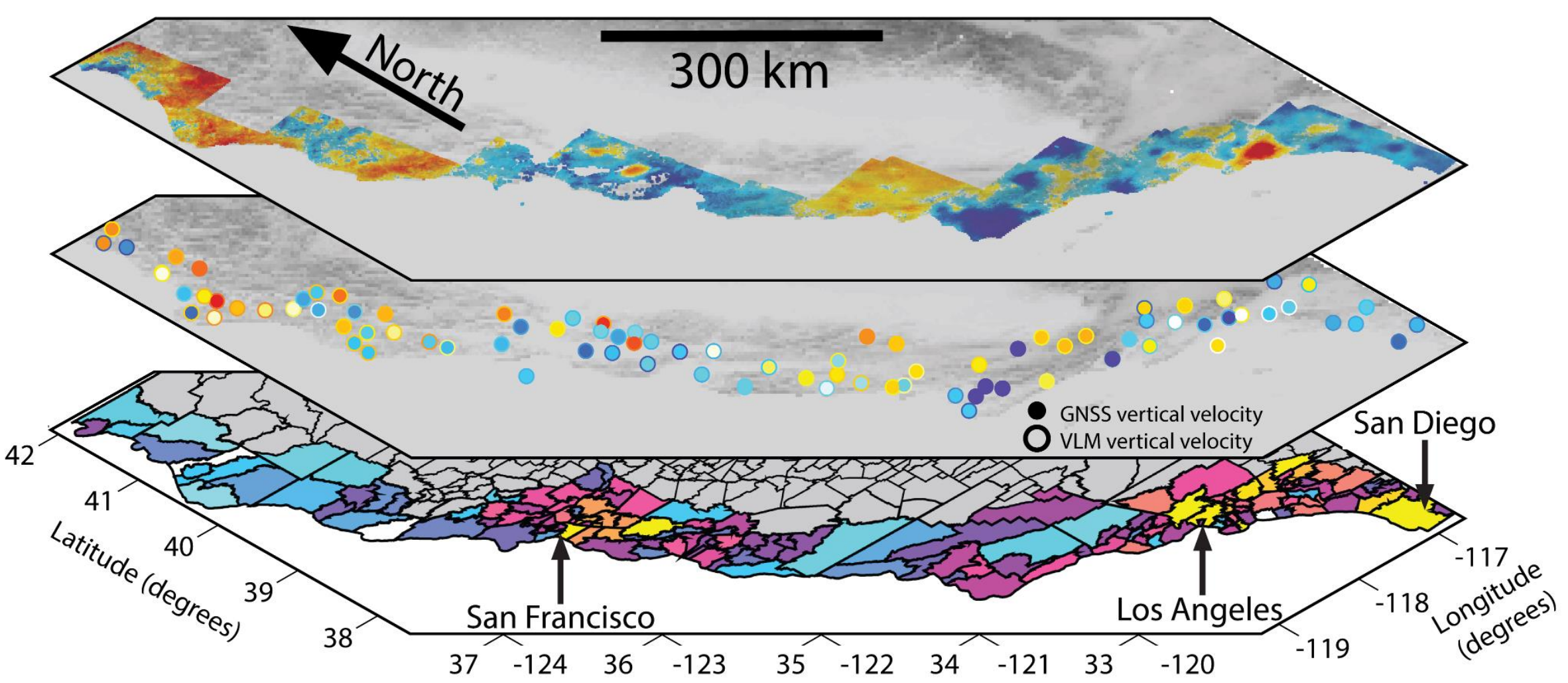
Blackwell, Shirzaei et al., (2020, Science Ad)

CALIFORNIA COAST VLM RATE



Blackwell, Shirzaei et al., (2020, Science Ad)

CALIFORNIA COAST VLM RATE

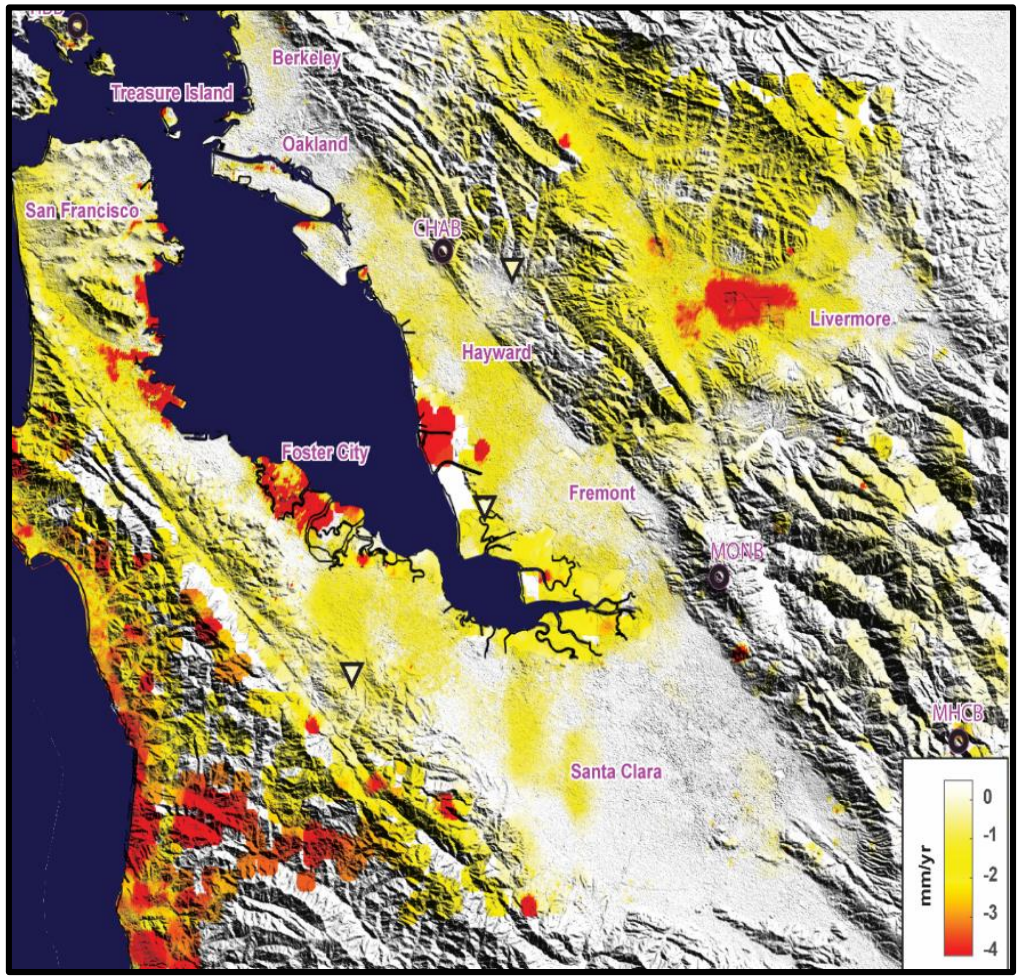


Blackwell, Shirzaei et al., (2020, Science Ad)

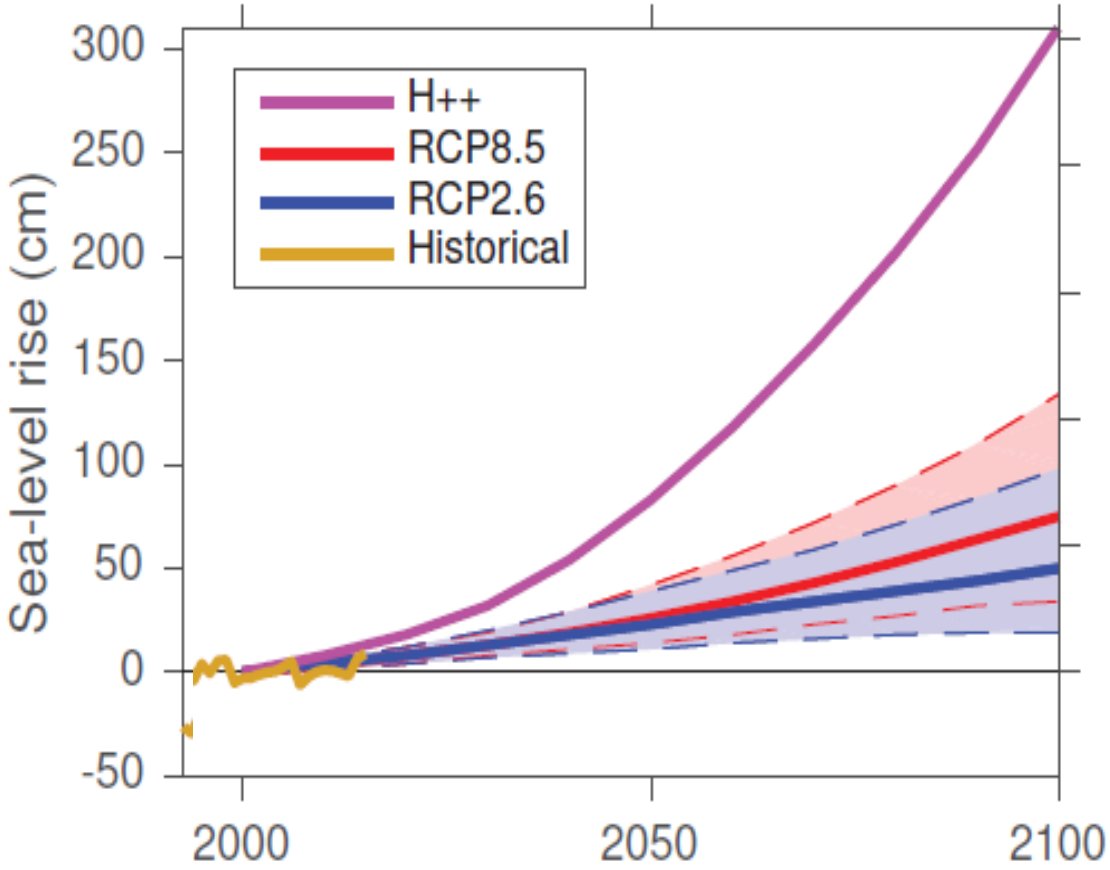
TAKE-HOME MESSAGES

- Combination of multi-track InSAR and GNSS data enables measurement of VLM at 1000 km extent, 50 m resolution, and mm level accuracy.
- The first high-resolution map of VLM in the global reference frame for the entire coast of California was presented.
- Many highly populated, low elevation coastal communities in California are subsiding. 4.3-8.7 million people are likely to be exposed to subsidence.
- SAR data with global coverage are publicly available, and it is technologically feasible to compute worldwide maps of coastal VLM rates at management-relevant resolution (~10^1 m).

SAN FRANCISCO FUTURE INUNDATION HAZARDS

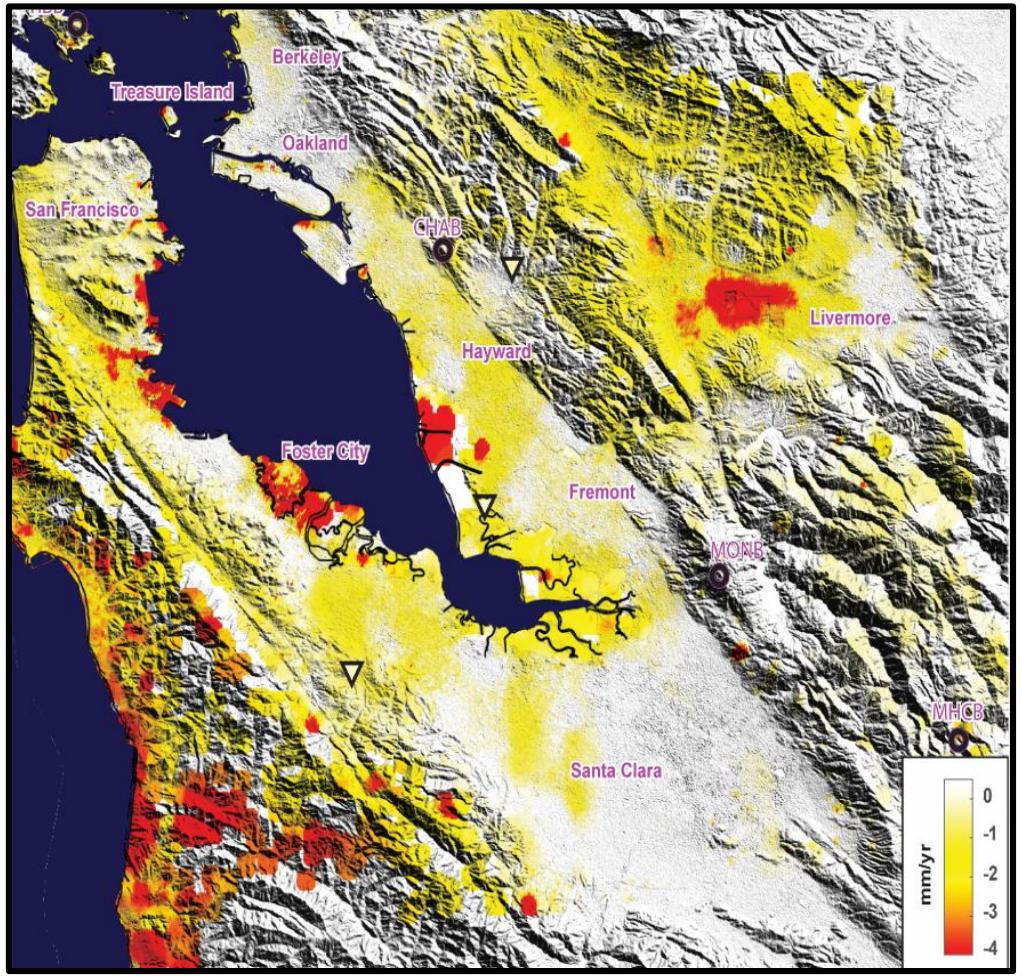


Shirzaei & Burgmann (2018, Science Ad)

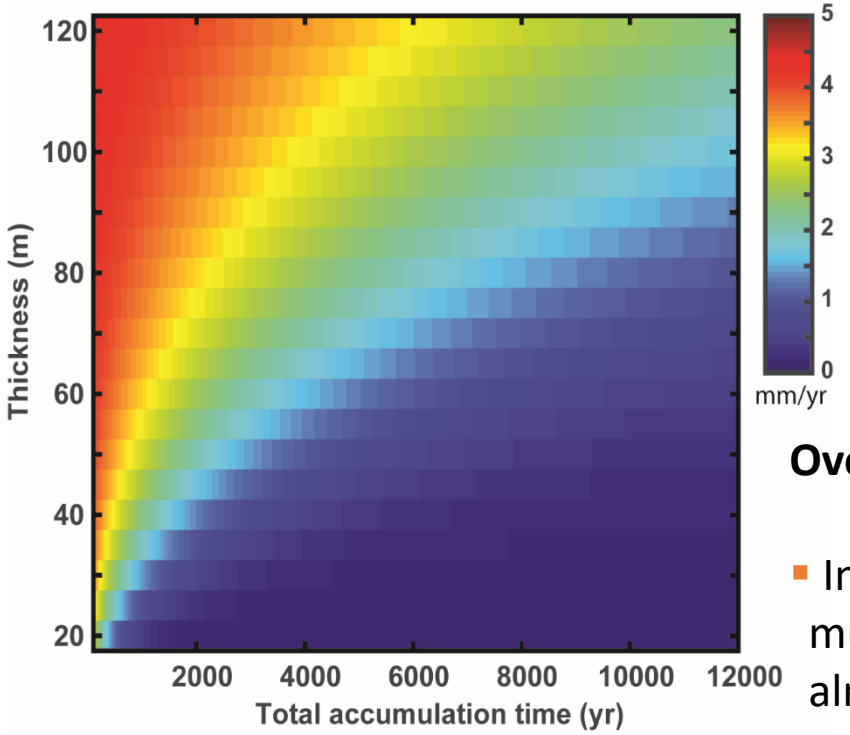


Griggs et al., (2017)

SAN FRANCISCO FUTURE INUNDATION HAZARDS



Shirzaei & Burgmann (2018, Science Ad)



Kooi and De Vries (1998)

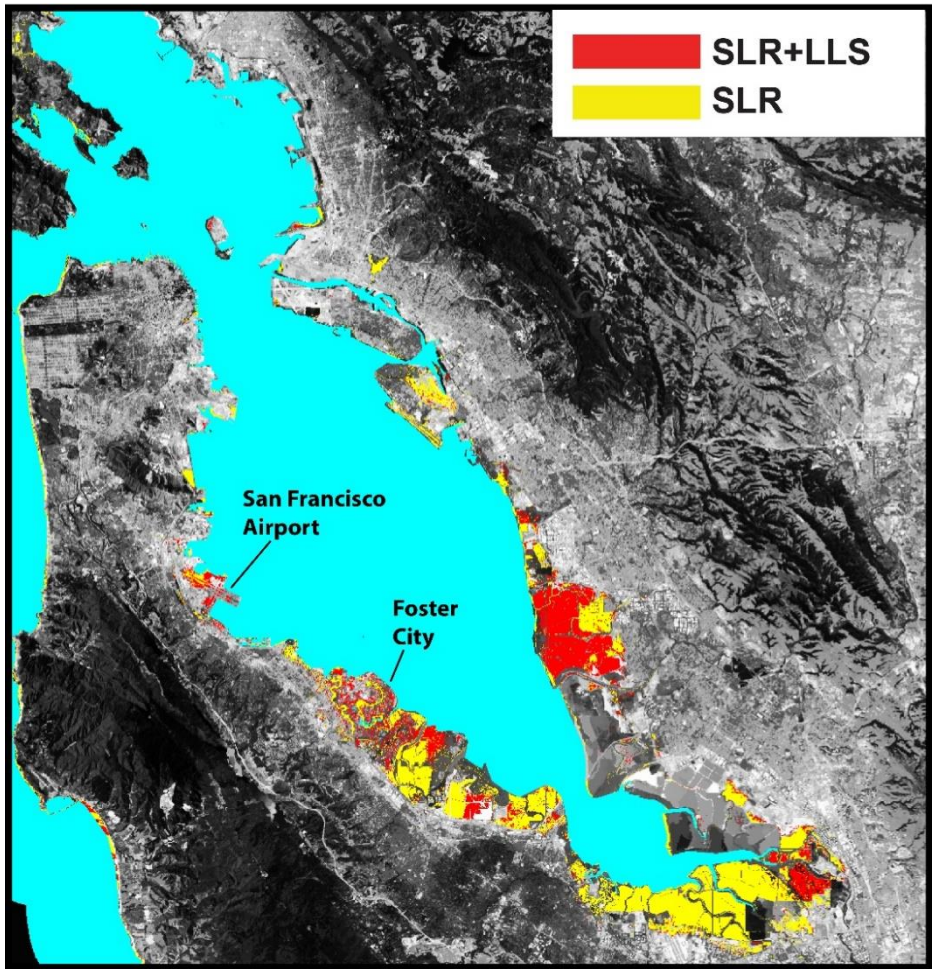
Over the next 100 years:

- In area of Holocene Bay mud, compaction rate is almost constant.
- In areas of landfill, compaction rate changes by 5 - 14% given thickness of 10 - 30 m.

SAN FRANCISCO FUTURE INUNDATION HAZARDS

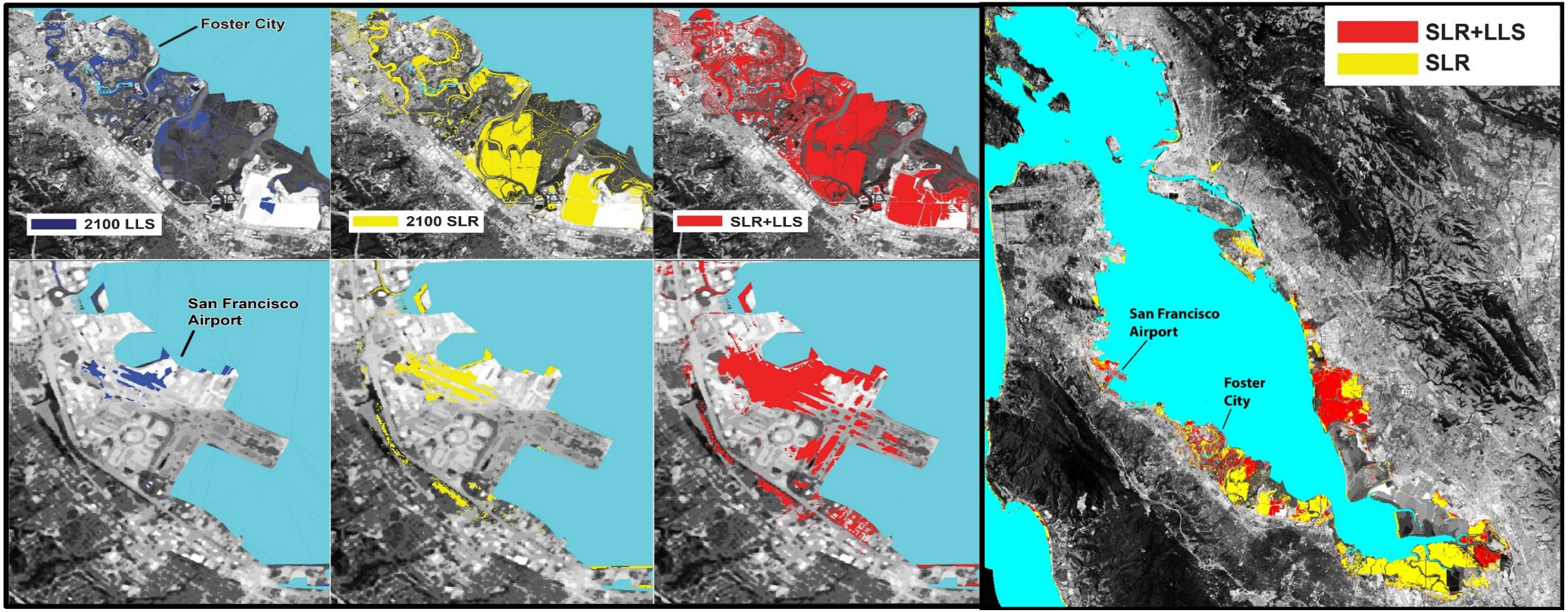
Inundated area by year 2100 under RCP 8.5:

- Assuming only SLR an area of 168 km^2 will be inundated.
- Including LLS the inundated area will increase to 218 km^2 .



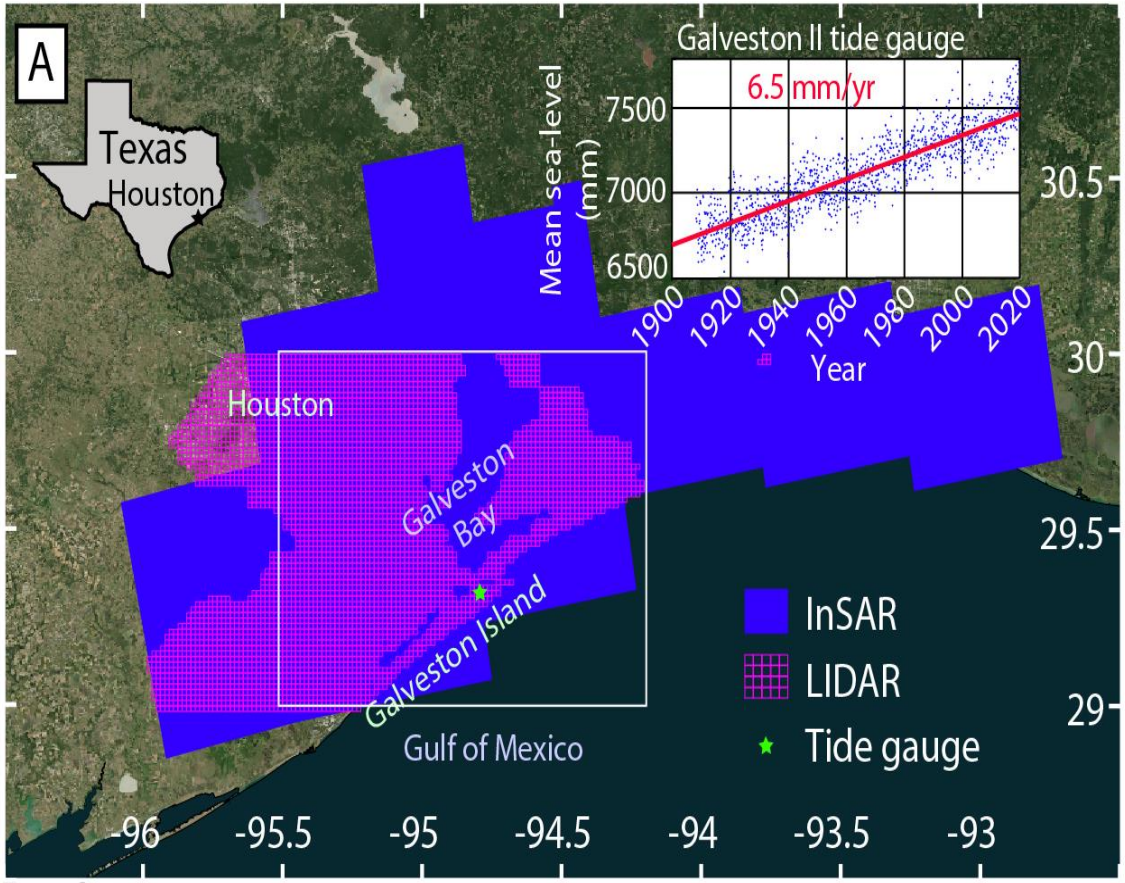
Shirzaei & Burgmann (2018, Science Ad)

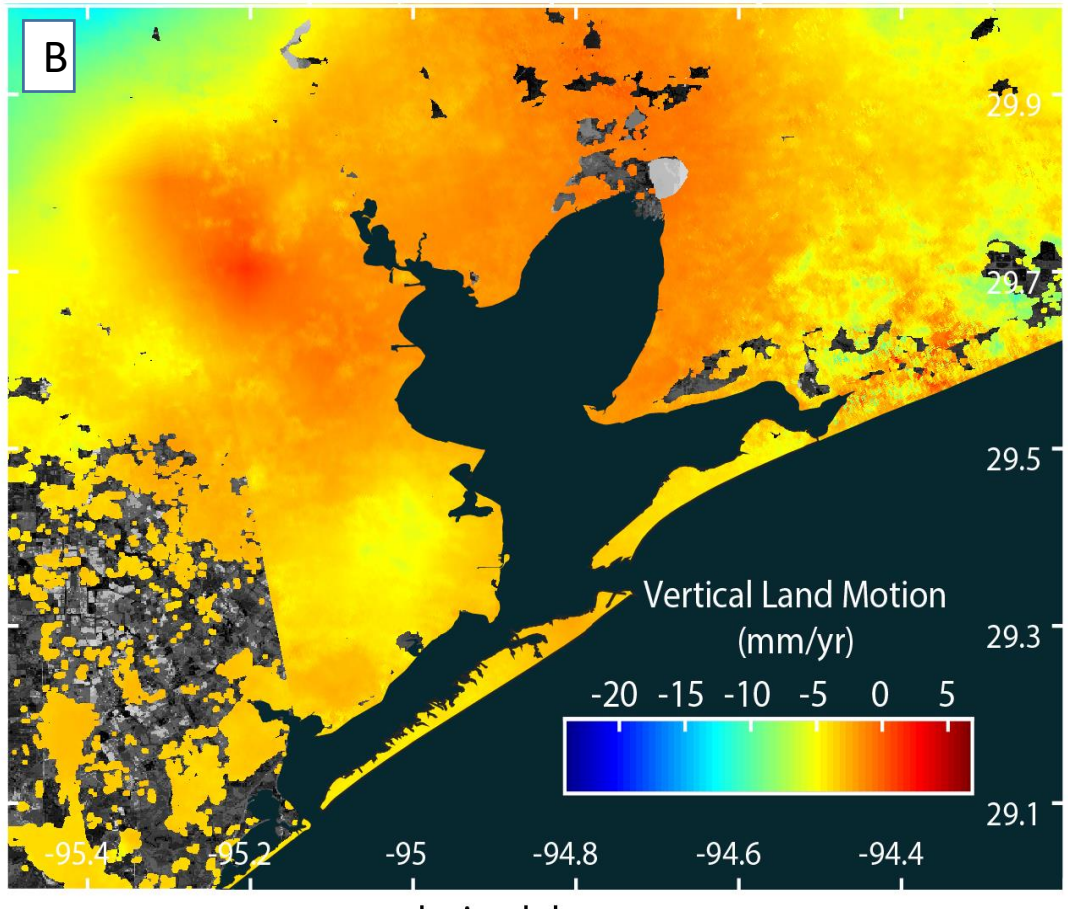
SAN FRANCISCO FUTURE INUNDATION HAZARDS



Shirzaei & Burgmann (2018, Science Ad)

HOUSTON, TEXAS CASE STUDY

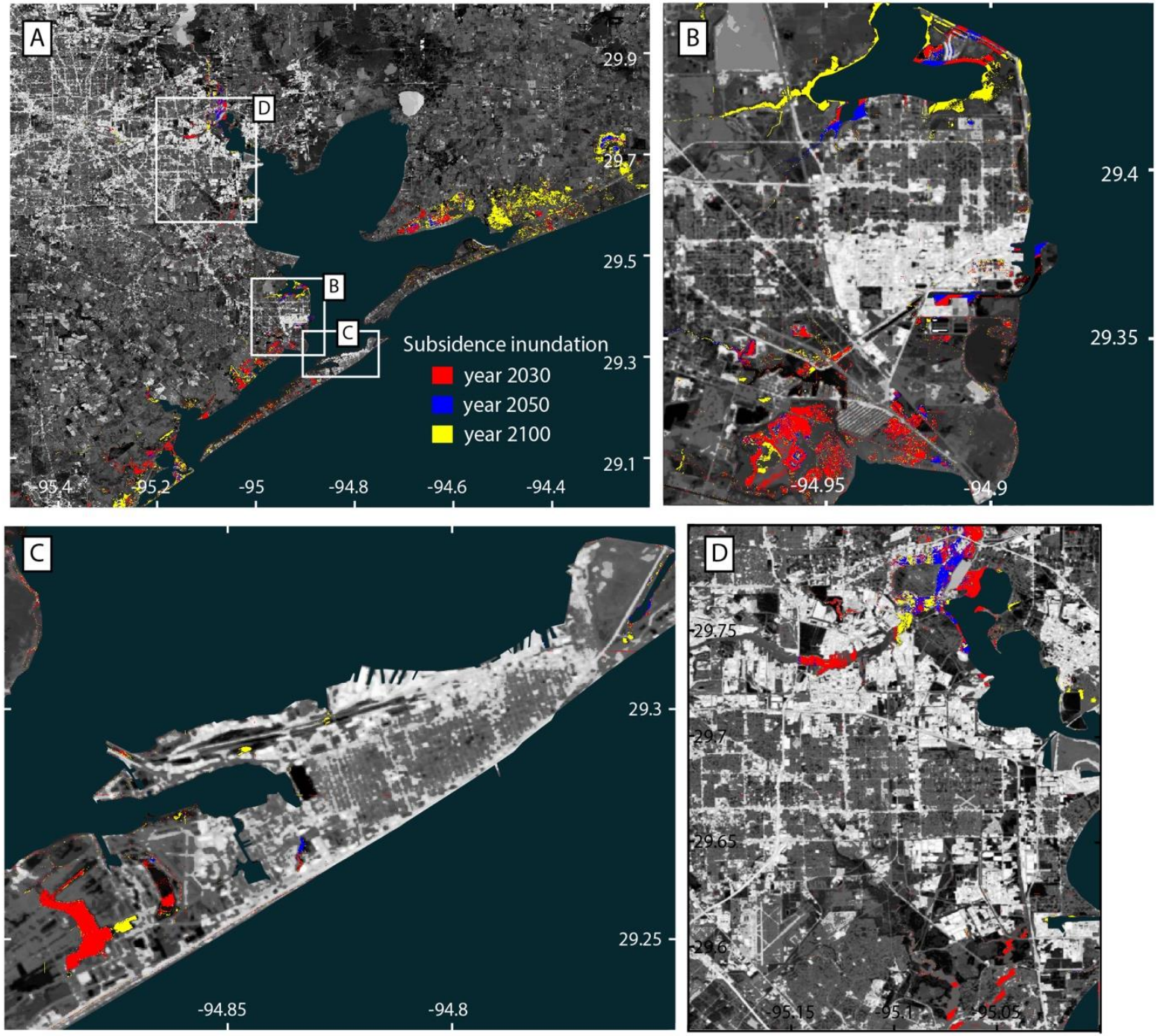




Miller & Shirzaei (2020, GRL, submitted)

SUBSIDENCE INDUCED INUNDATION

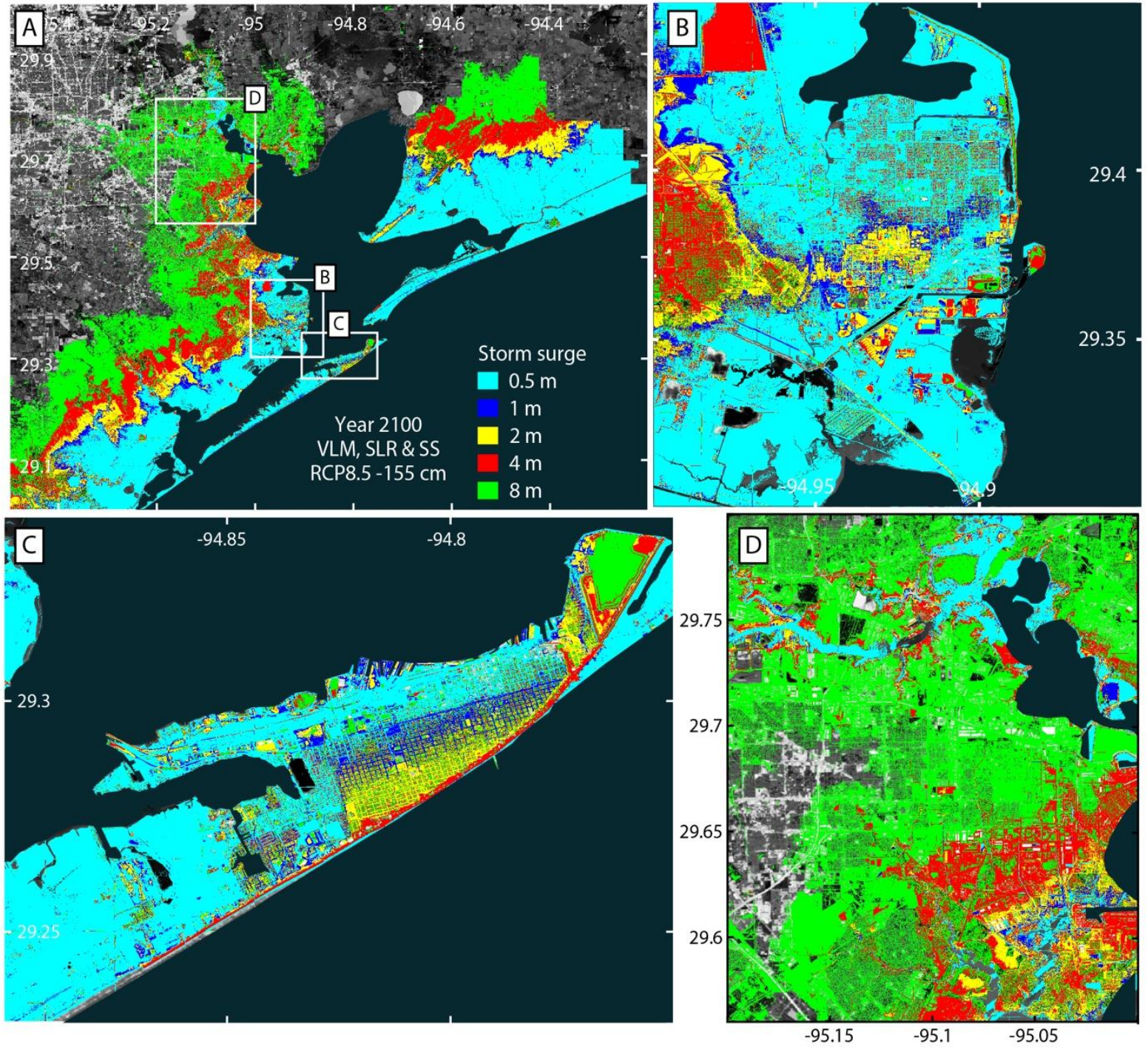
- By the year 2100, subsidence alone causes an area of **76** km^2 to inundate.



Miller & Shirzaei (2020, GRL, submitted)

SUBSIDENCE, STORM SURGE, SEA LEVEL RISE INDUCED INUNDATION

- By the year 2100, under the worst-case composite scenario of an 8-meter storm surge, subsidence, and the SLR RCP8.5, the total inundated area is **1,156** km^2.



Miller & Shirzaei (2020, GRL, submitted)

TAKE-HOME MESSAGES

- Even without any future global sea-level rise, flooding hazards may increase due to continued coastal land subsidence.
- In San Francisco Bay, an area of 125 km^2 – 429 km^2 will be subject to inundation and flooding by 2100 due to SLR and LS.
- In Houston, an area of 186 km^2 – 1157 km^2 will be subject to inundation and flooding by 2100 due to SLR, LS and SS.